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Lithium-based Battery System Management and Balancing

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For the degree of Master of Science

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LITHIUM-BASED BATTERY SYSTEM MANAGEMENT AND BALANCING

A Thesis

Submitted to the Faculty

of

Purdue University

by

William Joel Schmidt III

In Partial Fulfillment of the

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of

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I dedicate this work to my family for their support and guidance throughout my endeavors.

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ABSTRACT

Schmidt III, William Joel. M.S., Purdue University, December 2011. Lithium-based Battery System Management and Balancing. Major Professor: Jeffrey W. Honchell.

This thesis builds upon previous work completed for the design and evaluation of active lithium battery system management. Simulations were performed to provide a comparison for the hardware that was designed, built, and tested. An analysis of the simulation and hardware results was completed to support or disprove the initial hypothesis. A DC-DC converter was used as the source for the balancing current. Lithium polymer batteries with a 5Ah capacity were used for testing the designed hardware. The findings showed that there is a reduction in the system voltage swing during balancing as well as less time taken to decrease the imbalance delta.

CHAPTER 1. INTRODUCTION

The increasing use of lithium-based battery cells in electric and hybrid vehicles has presented many challenges in terms of system design and safe use of the cells. These challenges include the unique characteristics of the battery chemistry that requires new technologies for monitoring and maintaining the battery cells during use, real time decision making based on measured parameters, and optimizing the overall system to obtain the maximum performance.

1.1 Scope

The careful use of a lithium-based battery systems in electric and hybrid vehicles is required due to the unique characteristics of lithium cell chemistry. A properly maintained battery system is always balanced. This balancing occurs when each cell in the battery system is brought to the same state of charge. This level is often based on the voltage of the cell. The unbalancing of a lithium-based battery system is the result of numerous discharging and charging cycles during which the state of charge of each battery begins to vary slightly. Many variables that can lead to this unbalancing include temperature, individual cell chemistry, and the use of a battery management system. This research will focus on the battery management system as a tool to balance the battery cells, providing a method for extending the energy usage and life of the batteries. Two concepts based on previous designs will be utilized in an effort to create a new approach for an efficient system (Bonfiglio, 2009; Karnjanapiboon, 2009). The design and testing of the new battery management system approach will utilize smaller capacity battery cells as well as limit the number of cells to eight to prove the concept.

1.2 Significance

The balancing of a lithium-based battery system has one very large benefit. As the batteries are charged and discharged their capacity is reduced. The unbalanced discharging and charging of cells accelerates the time before the cell capacity is diminished to the point of the system being no longer useful or decreases the time before failure. The equal charging and discharging of the individual cells allows the end user to obtain the maximum energy and life out of the battery system as a whole, eventually saving cost and environmental resources. While battery energy capacity, weight, and reduced harm to the environment are continually being improved, the technology is still slower progressing than the technology using the batteries as an energy source. Therefore, the utilization of the present battery technology is of great importance.

1.3 Research Question

Is an active battery cell management method more effective at maintaining system voltage and requiring less time than a passive method?

1.4 Assumptions

This research is conducted and conclusions are drawn acknowledging the following assumptions:

- The results are accurate to within the tolerances of the components used in the designed circuitry.
- The battery cells used in the study are new.
- Not all of the batteries have identical internal chemistry, resulting in variations that are uncontrollable.

1.5 Limitations

This research is conducted acknowledging the following limitations:

- The study will focus on cell balancing while the batteries are not being used to power a load.
- The battery cells being used are of a specific chemistry and specific ampacity.
- The temperature used for testing will be limited to an average ambient temperature of 20-25 degrees Celsius as set by the locked thermostat in the room.
- Traceable, calibrated equipment is not available for use in this study.

1.6 Delimitations

This research is conducted acknowledging the following delimitations:

- Other ampacities of battery cells are not used in the study.
- Other battery chemistries are not used in the study.
- Temperatures outside the range of a typical room will not be used in the study.

1.7 Definitions

Active cell balancing - the transferring of energy via a transfer medium from one series connected battery cell to another (Bonfiglio, 2009).

State of Charge (SOC) - the percentage of available potential energy contained within the battery cell.

Cell Imbalance - A condition where the battery cells in the system are not at the same state of charge.

Watt-hour - A unit of constant energy, described as energy = Joules/hour.

1.8 Summary

This chapter has provided an overview of the research contained within this thesis as well as its purpose, assumptions, limitations, delimitations, and definitions. The following chapter will introduce and examine research that has been completed on the subject and provide a starting point for further investigation.

CHAPTER 2. LITERATURE REVIEW

This chapter gives an overview of a battery management system (BMS), the basic operation, and some of the challenges associated with the design process. The chapter introduces the literature and the associated work that has been completed both recently as well as previous work. The overall goal of this chapter is to provide a basic understanding of the topic as well as describe the new direction to be taken during the research on the subject.

2.1 Overview of a Battery Management System

A battery management system is a system that monitors the cells in a series connected string for a number of variables. These variables can include individual battery voltage, state of charge, and total pack voltage. The BMS usually has protection mechanisms built in for over and under voltage situations, but can also include temperature sensing and failure modes of batteries. Some BMS designs will also incorporate a method of communicating data back to a central interface for the user to see or a computer for analysis later. Asumadu, Haque, Vogel and Willards (2005) show a design for a BMS with a very clear communications protocol to be transmitted back to a laptop or PC.

An example of a general BMS system is shown in Karnjanapiboon, Jirasereeamornkul, and Monyakul (2009), where the cells are balanced through flyback DC-DC converters using a central controller. This system does not communicate back to a PC or other data logging device to aid the end user in troubleshooting or during general use of the battery pack. It also does not give an indication of whether or not a failure has occurred. More examples of general and more complex systems that range from the simple passive to complex active systems can be seen in Kutkut and Divan (1996). The wide range of complexity in the circuits gives an idea of some of the challenges that will be encountered in the design process of a BMS for a larger battery system.

2.2 Need for a Battery Management System

The need for a battery management system in lithium based battery systems is very high due to inherent imbalancing issues associated with the charging and discharging of the battery pack. Baughman (2008) gives a few indicators of the characteristics that cause this:

> Imbalanced cell voltages are caused by differences in cell capacities, internal resistances, chemical degradation, and inter-cell and ambient temperatures during charging and discharging (p.1).

The main goal of a battery management system is to minimize this imbalance within the pack to extend the life of the batteries and to obtain the highest performance.

In the cases of the testing performed in Moore (2005), the battery systems had energy throughput in the megawatt-hour range. Improving the efficiency of the BMS to reduce the wasted energy in the passive balancing method could have a significant effect on the energy throughput of the battery system. The cells being used in this thesis have a life expectancy of about 500 cycles per the manufacturer. In the case of the cells used in this thesis the theoretical energy throughput is:

$$Energy = (3.7V * 8\,cells) * 5Ah * 500\,cycles = 74kWh$$

If the balancing were to account for even one percent of the total throughput, that would be 740Wh. This would lead to (740Wh/148Wh) five fewer cycles the battery system would not be able to do.

Another useful aspect of a BMS would be to alert the user of a possible failure in one or more cells so the risk of damage or injury can be avoided. The risk of damage or injury is of higher importance if the battery pack is to be used in a vehicle. An extreme case could be identified as losing control of the car or the battery system catching on fire resulting in an explosion or lithium fire.

2.3 Types of Battery Management Systems

There are two types of BMSs that are commonly found in commercial and industrial lithium battery based systems. Each type of system has different benefits that vary among cost, efficiency, and complexity. The first style of BMS is a passive system. Battery stacks that are being produced today largely use a passive cell balancing method (Bonfiglio & Roessler, 2009). The passive system is more basic in the fact that it only operates during the charging cycle of the battery stack. Kutkut (1996) states a disadvantage of the passive system as:

> One drawback of this approach is that the recovered energy is converted into additional losses in shunt elements (p.1).

The wasting of energy effectively leads to overall lower system efficiency, counterproductive to the idea behind electric vehicles.

The second type of BMS is the active management system. The active management system is more complex than the passive system. It has the ability to be far more efficient in charging the cells while taking a shorter amount of time. It was stated that the difference in charging time of a 24V@60Ah battery was 6.4 hours for a balancing system versus 7.6 hours without the balancing circuit (Zheng & Zhao, 2009). Unlike the passive system where extra power is often wasted as heat, the energy is reused in the charging process.

Active BMS schemes range from a switched capacitor topology as shown in (Baughman & Ferdowsi, 2008) to a flyback converter topology as shown in (Bonfiglio & Roessler, 2009). The two active BMS schemes that will be examined before the initial design process are the flyback converter and bi-directional DC linked bus, with the following figures showing the design for each. These schemes include:

- The flyback converter in Figure 2.1 (Bonfiglio & Roessler, 2009)

- The bi-directional DC linked bus in Figure 2.2 (Karnjanapiboon, et al. 2009)

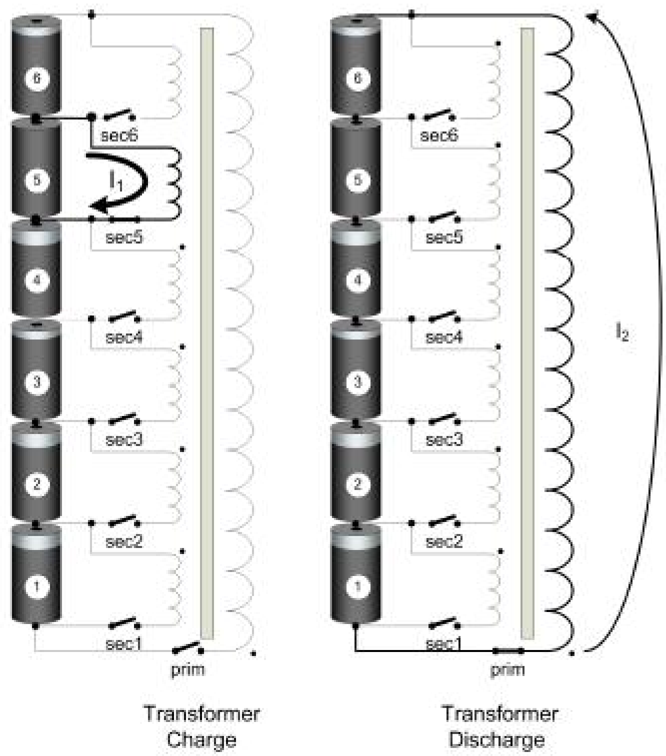

Figure 2.1. Flyback Converter Balancing Scheme (Bonfiglio & Roessler, 2009)

An advantage of the flyback converter scheme, as shown in Figure 2.1, is the automatic nature of the balancing. When the primary of the transformer is being switched, the secondary with the lower cell voltage will naturally draw more current, receiving a charging current inversely proportional to the cells SOC (Moore & Schneider, 2001). This method of operation requires that all secondary switches are on while the primary is being switched. The other mode of operation is when only one secondary is used to provide a balancing current. The flyback converter balancing scheme allows for the use of just n+1 number of switches in the balancing circuits. However, as noted in (Moore & Schneider, 2001), this somewhat similar scheme requiring individual secondary windings for each battery cell is complex in design due to transformer construction and the switches. The maximum number of cells would be fixed as adding more secondary windings could not be easily added (Moore & Schneider, 2001). An example of this balancing scheme is shown in Figure 2.1.

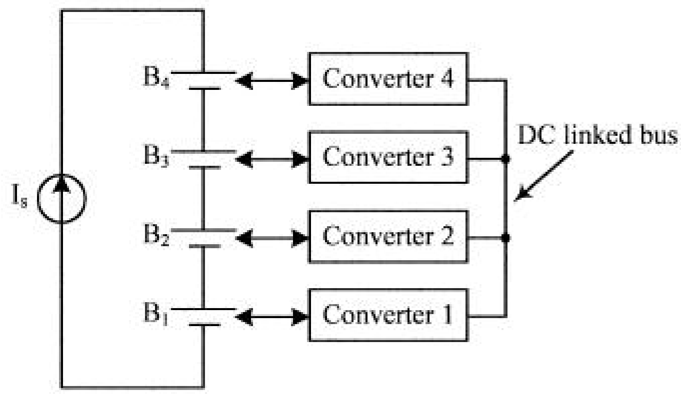

Figure 2.2. Bi-directional DC Linked Bus Balancing Scheme Block Diagram(Karnjanapiboon et al., 2009)

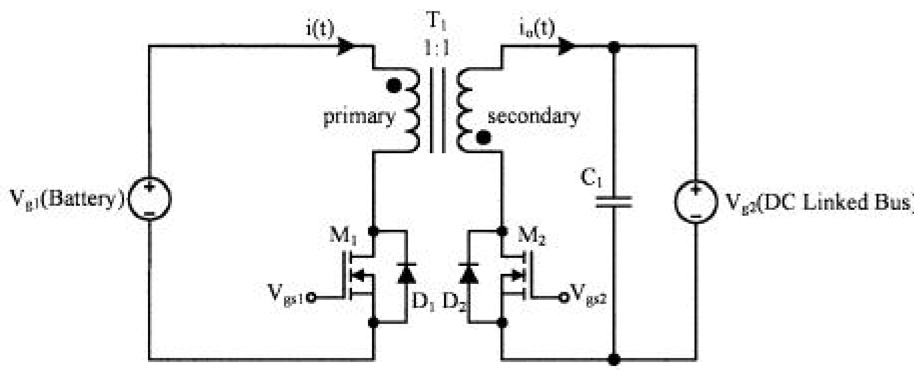

Figure 2.3. Bi-directional DC Linked Bus Balancing Scheme Schematic(Karnjanapiboon et al., 2009)

The bi-directional DC linked bus scheme, as shown in Figure 2.2, has a advantages when compared to the flyback converter scheme. The first advantage is the switching transformer construction becomes very simple with a primary and single secondary for each cell. A schematic of an individual DC-DC converter is shown in Figure 2.3. The second advantage is the topology allows for transferring of energy from the highest charged cell to the lowest directly. The flyback converter requires that the energy transferred out of a single cell be used on the entire stack of cells. A disadvantage to this scheme is the number of parts increase by a factor of two due to the switches on both the transformer primary and secondary. The cell balancing in this scheme also does not have the inherent balancing current based on the cell voltage characteristic like the flyback converter does.

This study will focus on a variation of the DC linked bus scheme. A DC-DC converter will be utilized much like the DC linked bus scheme, however, instead of a circuit for each battery cell, a scheme will be used to connect the converter and cells to the DC bus through relays. The additional current supplied by the DC-DC converter will be within the manufacturers specification for charging the battery cells.

2.4 Operation of a Battery Management System

This section will cover the overall operation of each type of BMS to gain an understanding of why the active method of battery stack balancing is more desirable than the passive method. The passive system is very simplistic in its operation. The following steps are the process during the balancing cycle using a passive system.

1. Cell measurements are taken
2. The lowest cell is determined
3. The resistive elements are turned on to bleed extra voltage away from the individual cells
4. The entire pack continues to balance until all cells reach the lowest initial cell voltage

The limited number of steps in the list above show the simplicity of the passive system. The active system is far more complex due to more complex algorithms to determine what actions need to be taken as well as the circuitry required to perform the conversion of power from a higher DC voltage to the single cell DC voltage. Figure 2.4 below shows the DC-DC converter connected to a single cell. The extra voltage from the voltage conversion is transferred from the battery system to an individual cell resulting in a much greater effectiveness during the charging process versus the passive shunting method. The following steps represent the process during the standalone balancing or charging cycle in an active system.

1. BMS measures the state of charge for each battery cell
2. A decision is made on which cell is least charged
3. The least charged cell is connected to the supplemental DC bus
4. The DC-DC converter is turned on
5. After 22 seconds have passed the DC-DC converter is turned off
6. The cell connected to the supplemental DC bus is disconnected
7. Repeat steps 2-7 until all cells are charged to within the 25mV window

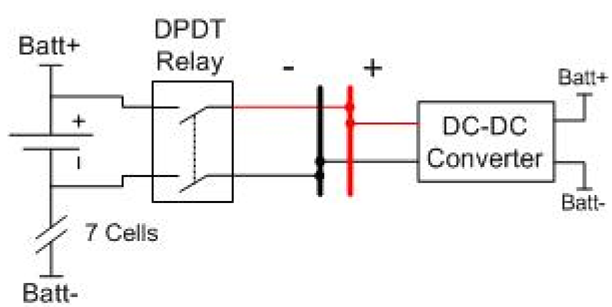

Figure 2.4. DC-DC Converter Single Cell Block Diagram

There are two large benefits to the active balancing system. The first benefit is the amount of energy wasted as heat is reduced to only the losses in the transferring of energy from the battery system to an individual cell. The second benefit to the active system is that the balancing can continually operate during the discharge cycle, allowing for continuous balancing that could ultimately lead to longer battery life. A possible downside to this scheme is that the system could continually run during the discharging of the batteries, effectively reducing the amount of power that could be delivered to the load. While the system is potentially having a beneficial effect on the battery system, this extra power consumption has the possibility to have a small detrimental impact. This problem can be remedied through the use of an intelligent control scheme that recognizes when the balancing action is not required.

2.5 Challenges of the Design Process

As mentioned before, the active BMS scheme is somewhat complex. While there are a few designs such as Karnjanapiboob et al.(2009) that can be constructed with almost all off-the-shelf parts, there are some designs such as Bonfiglio and Roessler (2009) that require very custom components. In order to keep the design time to a reasonable amount, more off-the-shelf components will be used. A large number of designs found in the literature search were based around a fixed number of cells. The system being designed for this study will utilize a fixed number of cells at eight. One possible source of difficulty in the development phase will be algorithm development for the main processor.

Another challenge in the design and testing process with the BMS is the tens of amps used to charge larger battery systems used in electric vehicles. The active BMS presents a more unique problem in the fact that the more of the balancing circuitry components will be required to handle the higher currents. The currents can be calculated through a proof much like Bonfiglio and Roessler (2009). The most important underlying theme to the testing process is safety. Lithium batteries can emit very harmful gases as well as produce a metal oxide fire if overcharged, over-discharged, punctured, or by any other misuse or abuse. The metal oxide fire is of particular danger due to the self-fueling nature of the reaction, limiting the methods of stopping the fire. During testing the battery cells were housed in a properly rated, sealed box or a ventilation hood to prevent contact with any part of a battery cell or emitted gases should an accident occur.

2.6 New Direction for the Battery Management System

The previous work completed on a battery management system for lithium based battery management systems has shown that there are good designs that accomplish the end goal. Some pieces of designs such as the basic design in Bonfiglio and Roessler (2009) and the communication aspects of the design in Asumadu, Haque, Vogel, and Willards (2005) could allow for an efficient design that can communicate all of the measured data back to a PC for logging of the data. Some of the desirable signals and data that would be useful for a user to have would be:

- Overall system voltage
- Individual battery voltage
- Any failures to battery cells
- State of charge
- Temperatures
- Diagnostic information

Likewise, some of the desirable functions of the management system would be:

- Overvoltage and undervoltage protection
- Disconnecting the charger in the event of a failure
- Ability to stop the load from drawing power from the battery if there is a fault condition

2.7 Summary

This chapter summarized the existing literature on battery management systems, and more specifically, active management systems. The literature has shown that while there has been work done in the area, there is room for improvement. This improvement can come in the way that some designs are being constructed, tested, and analyzed more in-depth, or it can come from combining the best aspect of each design into one.

CHAPTER 3. FRAMEWORK AND METHODOLOGY

This chapter will review the research framework, sample set, simulation design, hardware design, and the testing methodology used in this thesis. The purpose of this study is to develop a balancing system for lithium based battery systems. A large benefit to the balancing of these systems is guarding against damage improving the life of the battery cells(Bonfiglio & Roessler, 2009). Active balancing can also provide the benefit of less energy lost as heat during the balancing process.

3.1 Research Framework

The methods used in this study were designed to perform the balancing of the battery cells in the system using a flyback converter scheme. The following are a null and alternative hypotheses relating to the research question in Chapter 1.3.

- H_O - An active battery cell management method is less effective at maintaining system voltage and requires more time than a passive method.
- H_1 - An active battery cell management method is more effective at maintaining system voltage and requires less time than a passive method.

3.2 Sample Set

The experimental portion of this thesis was measuring the voltages of each battery cell in the system during the balancing operation. The battery system was comprised of eight cells for a total charged system voltage of 32V. The system was tested based on identical initial cell starting voltages determined by the first test completed. The voltages for each battery cell were taken at a set interval and recorded.

The collected data was analyzed after all testing for the set was completed. A set of simulations were also completed that will be covered in further depth in a following section of this chapter.

3.3 Testing Methodology

The testing methods for the experiment involved the use of a few basic laboratory devices including a multimeter, oscilloscope, and an ammeter. The data collection was completed mostly by the designed hardware itself and was analyzed after all tests were completed. The multimeter was used to measure the overall system voltage as well as individual cell voltages that are compared to the voltages measured by the balancing system. This will determine if the balancing system is operating within the design parameters. The ammeter was measuring the current output from the DC-DC converter when the DC-DC converter was enabled and disabled.

The tests performed on the active balancing system were set up in a random selection. The first step in the test was to begin with a balanced battery system. The battery cells were then unbalanced to different levels of state of charge, within a specified imbalance delta. The imbalance delta that was used for the hardware tests was 51mV. The system was turned on after the imbalance process and the battery cells were balanced to within a window of each other. The window between the lowest and highest charged cells was set at the same value as the simulations, or 25mV. Due to safety concerns when using lithium-based batteries, tests were performed in a ventilation hood. Figure 3.1 shows the hardware and batteries under the hood during a test.

After the balancing process was completed and the lowest and highest battery cell came within the 25mV window, the balancing system was turned off and final values were taken for the individual cell voltages. Due to the chemical reaction occurring within the battery cell, the final cell voltages were taken after five minutes had passed to allow for the cells to stabilize. The interval at which the variables were

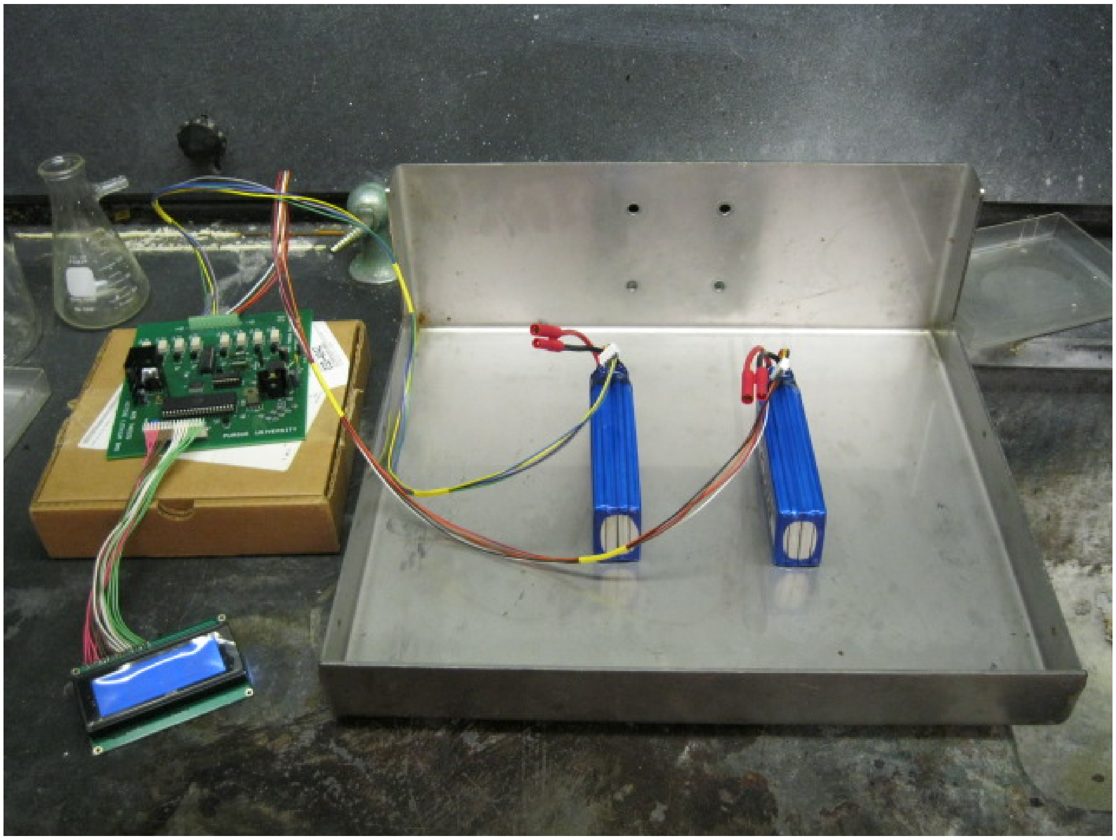

Figure 3.1. Hardware Testing in Ventilation Hood

measured during the balancing process had been determined after preliminary simulations were conducted and a generalized time for balancing based on the imbalance had been established.

Data collected during the tests were analyzed and included the battery voltages and the time for each balancing cycle. Software such as MATLAB or Excel was used to create graphic representation of the data as well as do any computations required. This data were used to alter parameters within the balancing system in order to optimize the time required for the balancing process. The optimization was focused primarily on the time taken by the system to perform the balancing. Any improvement would yield a shorter amount of time to reach the end of the cell balancing. Once the initial data were analyzed and the parameters of the system were changed, the test was completed again to determine if any improvement was made in the system.

3.4 Simulation of Design

As part of the validation of the hardware design, simulations were completed based on the balancing system examined within this thesis. MATLAB was chosen as the programming platform/simulation environment due to the amount of data to be processed. As part of the simulations for both topologies, a linear battery model was utilized. The linear model was chosen mainly due to the lack of a battery model for a specific commercially available cell that could be tested on the designed hardware. The linear battery model uses a constant slope to show the relation between the battery cell voltage and state of charge. The relationship is shown in Figure 3.2 below.

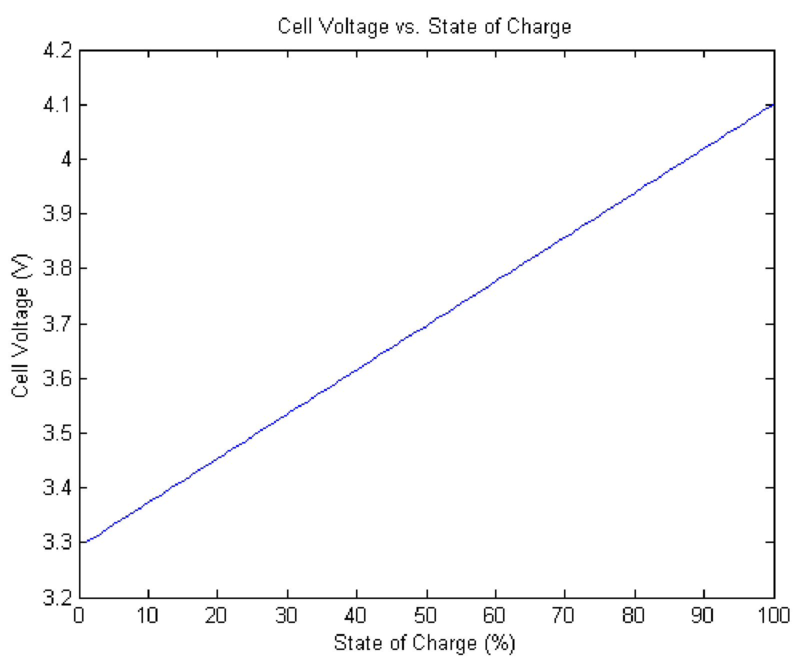

Figure 3.2. Cell Voltage and State of Charge Relation

The simulation was designed to use the output from the hardware tests as the input. The inputs to the simulation were the starting cell voltage, final cell voltage, and number of supplemental cycles conducted on each cell. From these inputs, the output was the theoretical final voltage and percent error between the hardware final cell voltage and simulation final cell voltage. To quantify the energy being transferred in the system, the energy unit of Joules was used. The reason for using the Joule is that this is an accepted standard measure for a unit of energy. To quantify how the simulation works the following equations will show the conversions and proofs for the relationships used.

$$1Wh = 3600J \quad or \quad 1J = 2.7777x10^{-4}Wh$$

$$Cell\ Capacity = 3.7V * 5Ah = 18.5Wh * \frac{3600J}{1Wh} = 66,600Joules/cell$$

$$Supplemental\ Joules/hour = 3.7V * 0.8A = 3Wh\ * \frac{3600J}{1Wh} = 10,800J/hour$$

$$Supplemental\ Joules/cycle = 10,800J\ * \frac{22sec}{3600sec} = 66J/cycle$$

$$DC - DC\ Joules/hour = 3.7V * 0.2A = 0.74Wh\ * \frac{3600J}{1Wh} = 2664J/hour$$

$$DC - DC\ Joules/cycle = 2664J\ * \frac{22sec}{3600sec} = 16.28J/cycle$$

$$V/Wh\, ratio = \frac{4.1V - 3.3V}{18.5Wh} = 43.24mV/Wh$$

$$V/J\ ratio = 43.24mv/Wh * 2.7777x10^{-4}Wh/J = 12\mu V/J$$

An example for the calculation of the energy flow into and out of a cell, the voltage change, and the final cell voltage is given as:

$$Cell\, X\ Joules = (\#\, of\ supplemental\, cycles * 66J/cycle) - (\#\, of\ total\, cycles * 16.28J)$$

$$Cell\ 4\ Joules = (39cycles * 66J/cycle) - (102cycles * 16.28J/cycles) = 913.44J$$

$$Cell\ 4\ V = 913.44J * 12\mu V/J = 0.01096V$$

$$Cell\ 4\ Final\ Voltage = (913.44J * 12\mu V/J) + 3.773V = 3.7839V$$

3.5 Hardware Design

The overall design goal of the active BMS was to make as simple a system as possible. Two preliminary configurations for the design were completed and are shown in Figures 3.3 below, and 3.4 on the following page. Figure 3.3 shows the initial design where a dedicated microcontroller was used to make voltage measurements for each cell. This microcontroller also controlled the photoMOS devices to connect the cell to the supplemental DC bus. Due to the fact that each microcontroller has control over the photoMOS devices, protection would have been required for each individual cell in the case that two cells connected to the supplemental DC bus accidently.

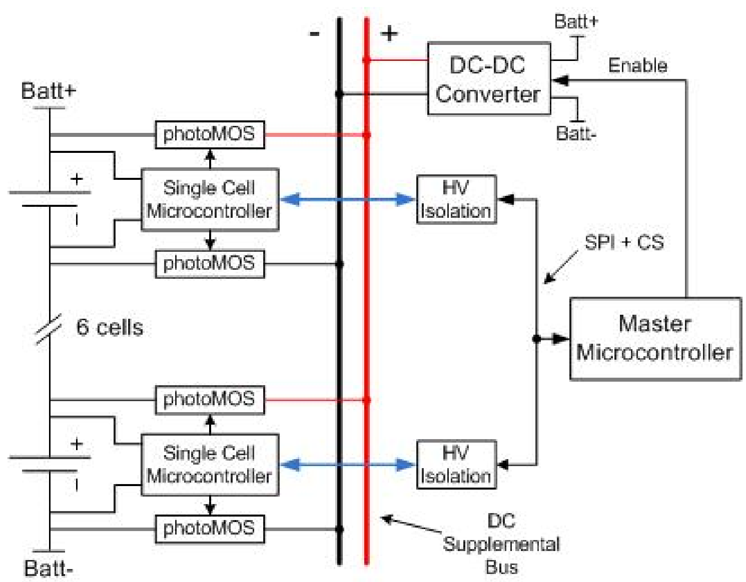

Figure 3.3. Individual Cell Monitoring Scheme

The second revision of the design, shown in Figure 3.4, decreased the parts count of the system dramatically due to only requiring one microcontroller for the cell voltage measurements. In terms of operation, the reduction from eight measurement devices to one device eliminated seven possible sources of variance. The final, assembled printed circuit board is shown in Figure 3.5.

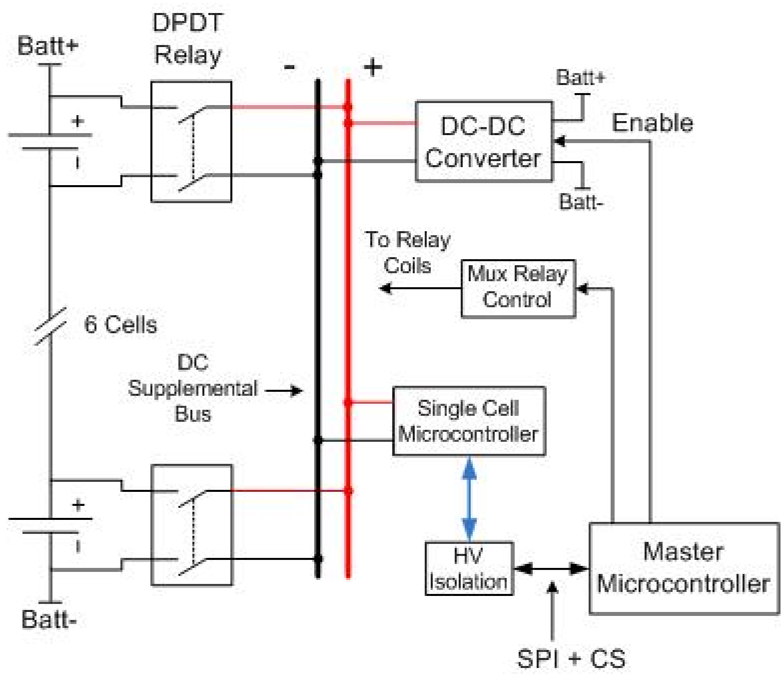

Figure 3.4. Relay Switching Monitoring Scheme

The second revision of the design used small signal relays to connect the measuring microcontroller and isolation IC to the battery cell. The master microcontroller used was an Atmel ATMega324P. This specific microcontroller was chosen for the available amount of pins for input and output, built in SPI communication, and the ability to perform differential analog input measurements through the internal analog-to-digital converter. The differential analog input was used in conjunction with the hall-effect current sensor to measure the current flowing into the battery cell connected to the supplemental DC bus. The microcontroller for the single cell measurement was an Atmel ATtiny461. This microcontroller was chosen for the built-in

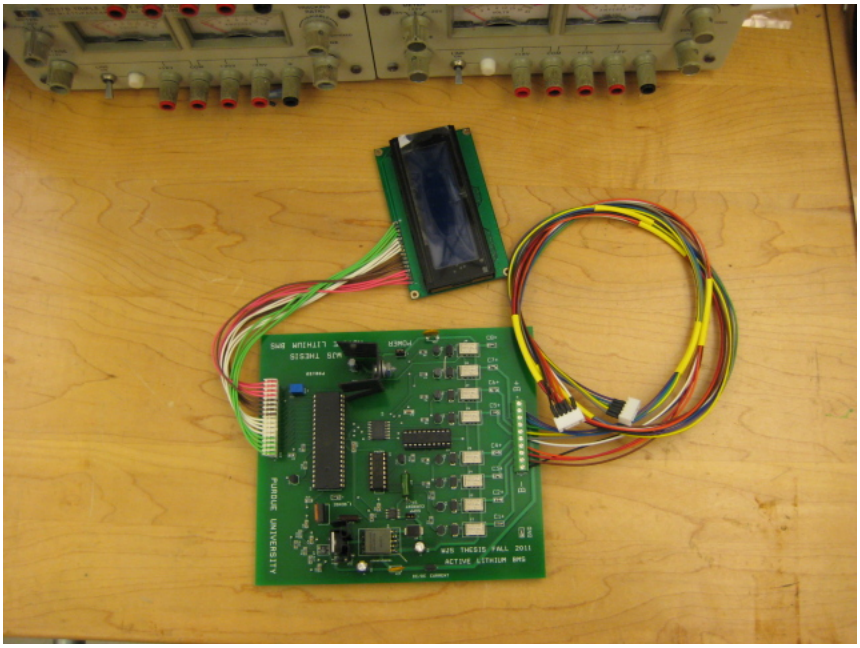

Figure 3.5. Final Printed Circuit Board

SPI capability and the internal analog-to-digital converter has the ability to do differential measurements. The schematics for the master and measuring microcontrollers are given in Figures 3.6 and 3.7.

When the single cell measurement is being performed, a differential measurement is being taken between the negative input, that is referenced to a 2.5V reference, and the positive input that is tied to battery cell positive. The 2.5V reference was chosen for the lowest possible cell voltage for lithium cells. The conversion result produces an output based on the equation:

$$Output = \frac{(V_{pos} - V_{neg}) * 1024}{V_{ref}} * GAIN$$

Therefore, for a battery cell voltage of 3.7V the analog-to-digital conversion result is:

$$Output = \frac{(3.7V - 2.5V) * 1024}{2.5V} * 1 = 491$$

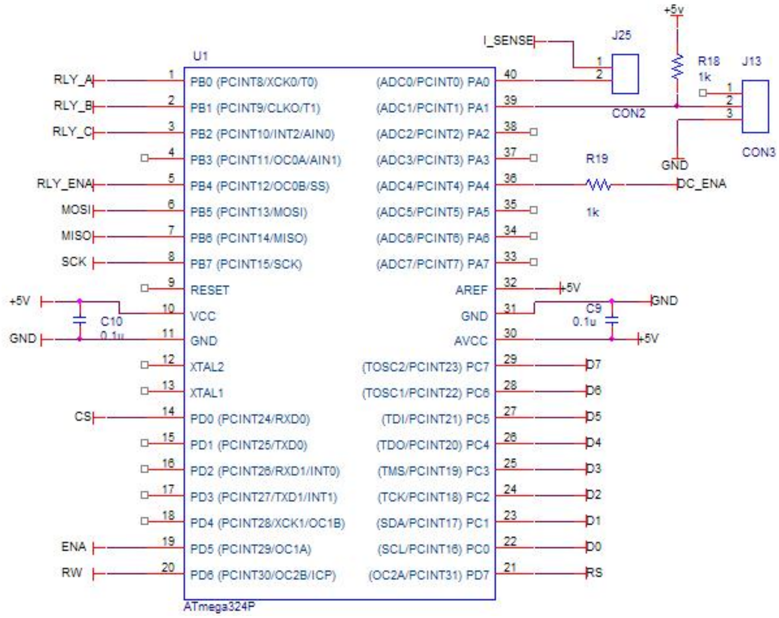

Figure 3.6. Master Controller Schematic

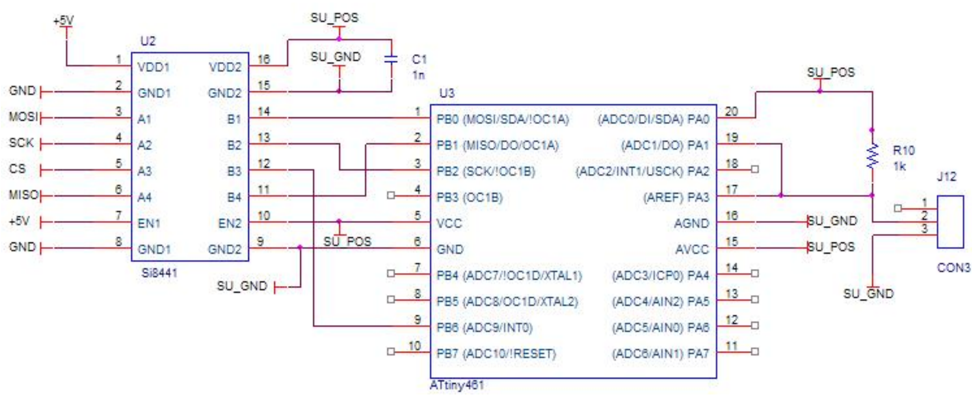

Figure 3.7. Measuring Controller Schematic

The DC-DC converter operates on an isolated flyback topology. This topology uses a transformer as the means of providing an output that does not share a common ground with the battery system, allowing for a connection to any battery cell in the system. The switching flyback controller used in the design was the LT3748. This specific controller was chosen mainly due to the feedback method. Typically the feedback is taken on the secondary side of the transformer that requires an isolating feedback circuit. The feedback method for the LT3748 uses the current in the primary as the source of feedback, reducing the part count and design complexity. Some possible problems with this type of switching controller could result in induced noise on the output and supply if caution is not taken in PCB layout and component selection. A schematic of the DC-DC converter is shown in Figure 3.8.

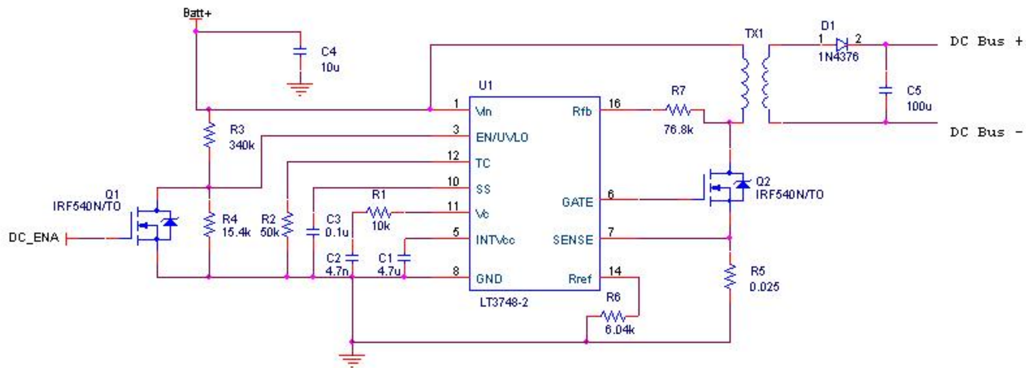

Figure 3.8. DC-DC Converter

Small signal relays were chosen for the method of connecting the battery cells to the measuring microcontroller and supplemental DC bus. The relays used were DPDT with contacts capable of 2A which is more than the DC-DC converter was able to supply. A four line by 20 character LCD was used as a method of displaying the measured voltages, the number of supplemental cycles each cell went through, and the difference between the maximum and minimum cell voltages. Figure 3.9 shows the LCD screen displaying the number of supplemental cycles performed on each cell and the maximum cell voltage delta. The numbers are the cell numbers and the D represents the amount of the voltage delta. All of the numbers displayed on the LCD are voltages represented as digital values from the analog to digital conversion.

3.6 Theory of Operation

The battery management system will, upon activation, measure each battery cell voltage and determine if any balancing action is required. After it has been

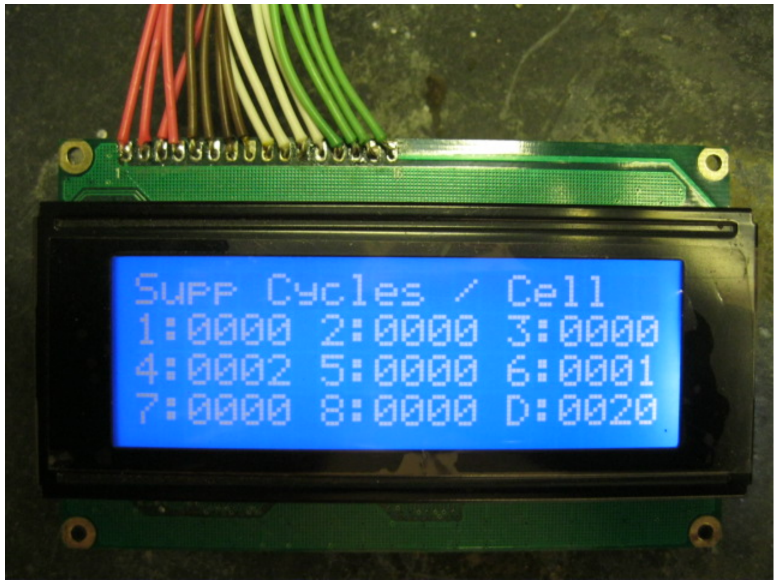

Figure 3.9. LCD Supplemental Cycles Screen

determined that balancing is required and the lowest cell has been determined, the cell is connected to the DC-DC converter output through the corresponding relay and the supplemental DC bus. An example of this connection is shown in Figure 3.10.

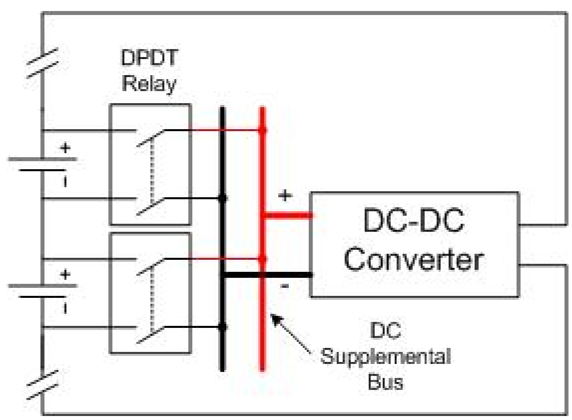

Figure 3.10. DC Supplemental Bus Connection

At the moment the selected lowest cell was connected to the supplemental DC bus, the DC-DC converter was disabled. A small delay exists between the closure of the relay contacts and the activation of the DC-DC converter to eliminate a hot switching case of the relay that could result in internal arcing and ultimately premature failure. Once the connection to the supplemental DC bus had been established the DC-DC converter was enabled. The lower voltage of the connected cell forces the DC-DC converter into a constant current mode of operation.

The cell with the lowest voltage is connected to the supplemental DC bus for 22 seconds then disconnected before another reading is taken of each cell to determine if another cell requires supplementing. While taking cell voltage readings, the system was also looking for faults such as a disconnected cell or a cell outside the operating limits. If a cell was found to have a fault condition, the system takes no balancing actions and notifies the user that a major error has occurred. A flowchart for the master microcontroller software is given in Figure 3.12.

3.7 Passive Method Verification

The passive method of balancing was tested to provide a baseline for comparison on the effectiveness of the active balancing method. The cells were set to a balancing current of 53mA, which is similar to the current used in (Moore & Stevens, 2005) for a commercial application. The hardware used for these tests was a combination of two series resistors and a switch as shown in Figure 3.11. The test would start with a voltage measurement being taken for each of the eight cells. The test was allowed to run for the same amount of time as the active method, or 60 minutes. After the 60 minutes had passed, the switch was opened and an open circuit voltage measurement was taken after the five minute settling time. A total of eight hours of data were taken across eight cells yielding 64 data points.

3.8 Threats to Validity

The lack of a number of battery systems could possibly be one of the threats to validity. Having only one set of hardware creates a very small sample set to verify the operation of the hardware. Another possible threat to validity is the environmental

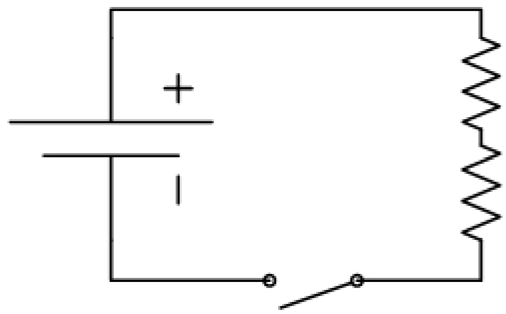

Figure 3.11. Passive Balancing Test Circuit

conditions in which the test is performed. Batteries have inherent properties that can affect the charging and discharging rates at different temperatures. While this variation can be very minor unless subjected to temperature extremes, the lack of a precisely controlled container presents the possibility. The untraceable voltmeter calibration is also a possible threat to validity.

3.9 Summary

This chapter has provided the framework of the experiment, key variables, and the hypothesis that is being tested. The general operation of the experiment was described as well as description of some of the instrumentation used during the testing. Furthermore, a short description of what the collected data is used for at a later time was presented. Any possible threats to the validity of the study were also presented to address any biases that may be acting on the experiment.

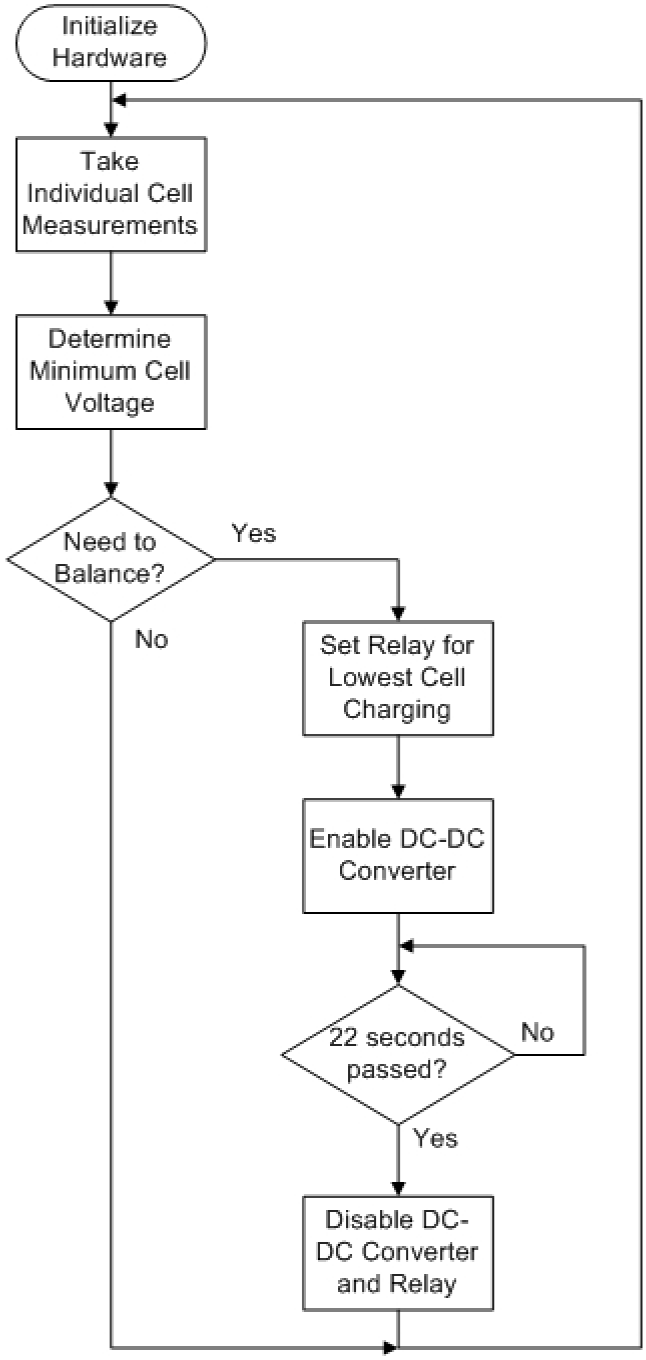

Figure 3.12. Master Microcontroller Software Flowchart

CHAPTER 4. RESULTS AND ANALYSIS

This chapter will cover the results from the simulations and hardware tests as well as present an analysis of the results to determine the effectiveness of the proposed active BMS scheme.

4.1 Hardware Tests

The hardware was tested for accuracy before running tests with live battery cells. The results from the initial accuracy tests showed that the hardware was performing within the designed specifications. The measuring microcontroller was able to measure the pseudo cell voltage from the power supply to within 2.5mV, or the error within the IC itself. The master microcontroller was also able to determine the lowest pseudo cell voltage with zero percent error. A table showing the accuracy test is given in Table 4.1.

Table 4.1 Hardware Accuracy Results

Cell Number	Set Voltage	Measured V	Percent Error(%)
1	3.755	3.756	0.0266
2	3.750	3.752	0.0530
3	3.758	3.756	-0.0530
4	3.761	3.760	-0.0266
5	3.759	3.757	-0.0530
6	3.757	3.758	0.0266
7	3.758	3.756	-0.0530
8	3.753	3.751	-0.0530

The hardware was then tested for proof of repeatability between tests. The battery cells were unbalanced to the same initial voltages for each test. The hardware was activated for 60 minutes, after which, the battery cell voltages were measured. Table 4.4 at the end of this chapter shows results from the hardware tests. A simulation was also completed with the same initial conditions to show the comparison. The results of the repeatability tests show that the hardware produces acceptable results across multiple tests. When a comparison is made to the simulation, the results are again acceptable for showing the relationship of the ending cell voltages. Table 4.2 gives an example of the starting and ending conditions as well as the simulation results and the percent error between the ending voltages of the hardware and simulation.

Table 4.2 Hardware Repeatability Results

Cell Number	Start V	End V	Sim End V	Percent Error(%)
1	3.796	3.782	3.783	0.0424
2	3.790	3.777	3.779	0.0579
3	3.808	3.796	3.787	0.2196
4	3.773	3.780	3.783	0.0944
5	3.820	3.808	3.799	0.2189
6	3.769	3.775	3.778	0.1000
7	3.820	3.808	3.799	0.2189
8	3.795	3.779	3.779	0.0000

At the end of every test the cells were allowed to rest for 5 minutes before the voltage reading was taken. The graph in Figure 4.1 shows an example of cell three during one of these five minute periods with voltage measurements taken every 30 seconds. As can be seen, the cell settled at a higher voltage after the resting period.

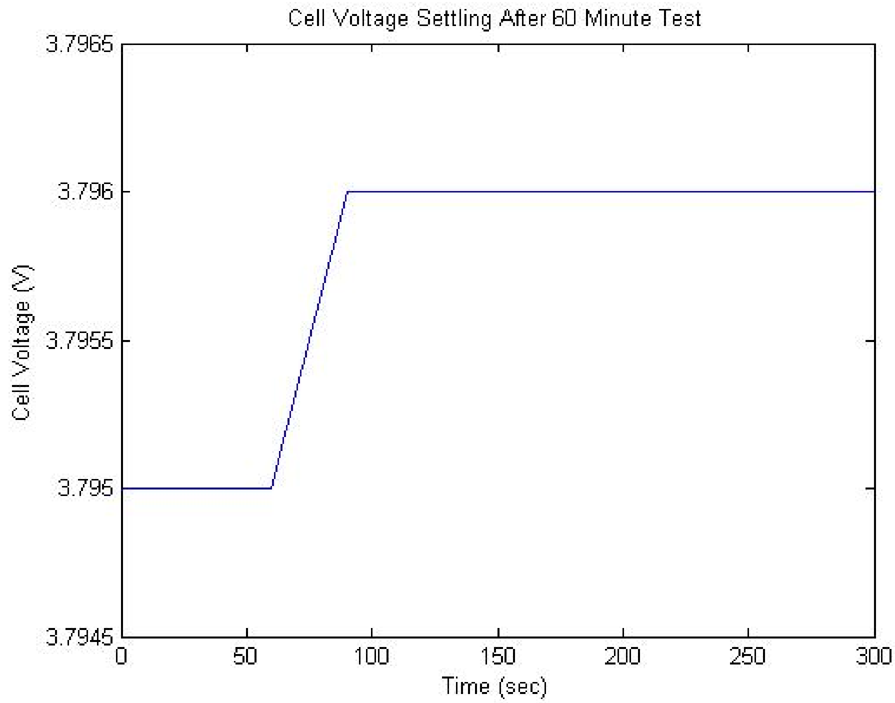

Figure 4.1. Post Test Cell Voltage Settling Measured with Voltmeter to 1mV

4.2 Simulation

The simulation was used to verify the hardware tests by using some of the results from the hardware as inputs. The number of supplemental cycles and final measured voltages were used in the simulation to determine the theoretical final cell voltage as well as the error between the hardware and simulation. The results in Table 4.3 show the average difference between the cells in hardware and simulation. The average differences in Table 4.3 show that some cells had a higher overall average than others. This could be caused by a number of factors including differences in chemistries between cells, the tolerance in parts used, or some other unmeasured variable. It should be noted that the cells that had an average difference of over 3mV were consistent, indicating that the hardware and software were indeed operating in a consistent manner. For example, 90% of the readings for cell three were either 10.XmV or 11.XmV.

Table 4.3 Hardware and Simulation Cell Differences

Cell Number	Average Difference(V)
1	0.00198
2	0.00055
3	0.01063
4	-0.00296
5	0.00822
6	-0.00346
7	0.00780
8	0.00027

The results of the passive method testing indicate that each cell had a slightly different rate of current consumption. While the current varied among the cells, it was consistent within the cell. For example, cell three consistently dropped 6mV for every hour the balancing current was enabled. Other cells had a more consistent 5mV drop every hour. This variation could be caused by internal characteristics of the cells or the tolerance of the resistors and switches used in the tests. For the purpose of a baseline comparison, the average of all voltage samples taken for the passive tests was calculated to be 5.38mV/hour.

The time taken by the hardware shows that this particular method of battery cell management and hardware design is more effective. The system voltage difference made by the balancing circuitry also shows that this method of battery cell management is more effective than a passive method. The following set of equations shows the results of the findings. As can be seen in the equations below, the active method produced about one third of the system voltage swing of the passive balancing method.

$$V_{act\ system\ V\Delta} = 30.371V - 30.305V = 0.066V$$

$$V_{pass\ system\ V\Delta} = 30.371V - 30.152V = 0.219V$$

$$Percent_{act\ system\ V\Delta} = \frac{V_{act\ system\ V\Delta}}{V_{system\ range}} * 100 = \frac{0.066V}{6.4V} * 100 = 1.03125\%$$

$$Percent_{pass\ system\ V\Delta} = \frac{0.219V}{6.4V} * 100 = 3.421\%$$

$$Percent_{system\ V\ difference} = \frac{V_{act\ system\ V\Delta}}{V_{pass\ system\ V\Delta}} * 100 = \frac{0.066V}{0.219V} * 100 = 30.13\%$$

Time was also a measure of the effectiveness of the active system over the passive. At the beginning of the active tests, the imbalance delta of the system was 51mV. The average imbalance delta after 60 minutes was 33.42mV resulting in an average of 17.58mV of correction per 60 minutes of active balancing. As can be noted earlier the passive balancing method only corrected for about 5.38mV/hour. Based on the time results from the two balancing methods it would take the active roughly 2.9 hours to correct for the 51mV delta and 9.5 hours for the passive. The active time was approximately 30 percent of the passive time, meaning the active system was three times faster than the passive method.

Table 4.4 Raw Hardware Test Data

Trial	Cell 1 (V)	Cell 2 (V)	Cell 3 (V)	Cell 4 (V)	Cell 5 (V)	Cell 6 (V)	Cell 7 (V)	Cell 8 (V)
6	3.784	3.778	3.797	3.781	3.809	3.775	3.808	3.782
7	3.785	3.779	3.796	3.780	3.809	3.776	3.807	3.780
8	3.783	3.780	3.800	3.782	3.810	3.774	3.809	3.782
9	3.783	3.779	3.798	3.781	3.808	3.776	3.808	3.779
10	3.785	3.778	3.800	3.782	3.809	3.775	3.809	3.781
11	3.784	3.780	3.799	3.781	3.807	3.774	3.809	3.780
12	3.784	3.779	3.798	3.781	3.808	3.775	3.808	3.782
13	3.785	3.780	3.800	3.780	3.807	3.776	3.807	3.780
14	3.783	3.778	3.801	3.782	3.808	3.775	3.808	3.781
15	3.784	3.779	3.800	3.781	3.809	3.776	3.807	3.782
16	3.786	3.781	3.799	3.780	3.808	3.774	3.807	3.780
17	3.783	3.780	3.798	3.782	3.807	3.775	3.808	3.781
18	3.784	3.779	3.799	3.781	3.809	3.774	3.808	3.780
19	3.784	3.781	3.798	3.780	3.808	3.774	3.809	3.779
20	3.785	3.780	3.800	3.782	3.807	3.776	3.808	3.781

CHAPTER 5. CONCLUSION, DISCUSSION, AND RECOMMENDATIONS

5.1 Conclusion

The purpose of this thesis was to examine an active method of battery cell balancing for lithium-based battery systems. Two topologies were reviewed to determine the design for the hardware that was ultimately constructed and tested. Simulations were also performed as a metric to validate the hardware operation. Overall, the active balancing system met the goal of being more effective at maintaining the system voltage and reducing the time taken to balance the cells.

5.2 Discussion

The overall system was able to perform the balancing of the battery cells. The goal of both better effectiveness of maintaining system voltage and shorter time were both simultaneously achieved. The post-balancing system voltage of the active balancing system was about 30 percent of the passive method and the time to reduce the cell imbalance delta was also about 30 percent of the passive method. There were not a statistically significant amount of runs to accept or reject either of the hypotheses. The results show a trend that, if more tests could be completed, the alternative hypothesis could possibly be accepted.

5.3 Recommendations

The overall hardware design could have a few improvements made to allow for easier operation and measurements as well as better operation. A dedicated switch to apply power to the master controller instead of a header-shorting jumper would allow for a more secure connection. The mechanical relays allow for a simple method of isolation from the master control circuitry and the battery cells and have a relatively high cycle life, however a solid state switching solution would essentially almost eliminate the chance of a relay failure.

In terms of the actual voltages measured during the tests, the use of traceable, calibrated equipment would be highly suggested for future work. This would be especially important for measuring and verifying key points in the system, for example the noise floor on the measurement microcontroller. The noise floor on the measuring microcontroller was variable from cell to cell by an average of 5mV. In general the noise floor on the measuring microcontroller was about 25-30mV$_{pk-pk}$ as measured by an oscilloscope. The voltmeter measurements are an averaging measurement, therefore, the noise is not as noticeable when measured with the meter. This noise is also a problem to be corrected in future work to ensure the accuracy of the data from the microcontroller. The repeatability of the system could be expanded to multiple systems to allow for concurrent testing to obtain more data for analysis and comparison. Using only one board and one set of batteries increases the amount of time spent on each test as well as reduces the validity of the experiment among a large population.

One area of concern with the hardware operation is the DC-DC converter. While following PCB layout guidelines for this type of circuit from the manufacturer, there are a few problems. The supplemental charging is still operational, although the effectiveness of the circuit could be diminished. The output capacitor of the converter continues to hold a charge after the converter has been disabled. When a cell is connected to the DC bus, the cell must force the capacitor to the same voltage. This action requires a settling time, which, was accounted for as much as possible during cell voltage measurements. A better solution to this problem could be using two sets of relays, one to connect the cell to the DC-DC converter, and one to connect the cell to the measurement microcontroller.

Another area of the design that could use improvement is switching of the transformer. When the MOSFET on the primary is switched on and off, overshoot is present on the rising edge of the pulse as well as the falling edge of the pulse. The overshoot is transferred through the windings in the transformer and produces a $4V_{pk-pk}$ spike on the output on both switching edges. This applies a large voltage to the cell and the measuring microcontroller twice every pulse. Oscilloscope screen captures are shown below for the output of the transformer, gate on the MOSFET, drain on the MOSFET, and source of the MOSFET.

The DC-DC converter has noise present on the output that needs to be examined in more depth to facilitate a cleaner current source for the battery than it currently is. One possible solution to the noise that could be looked at in future work would be inserting a linear regulator after the DC-DC converter output. The system could also be equipped with a better method for displaying/gathering data than the LCD used. Data collection over USB would allow for a more in-depth look at the cell behavior throughout the entire balancing process.

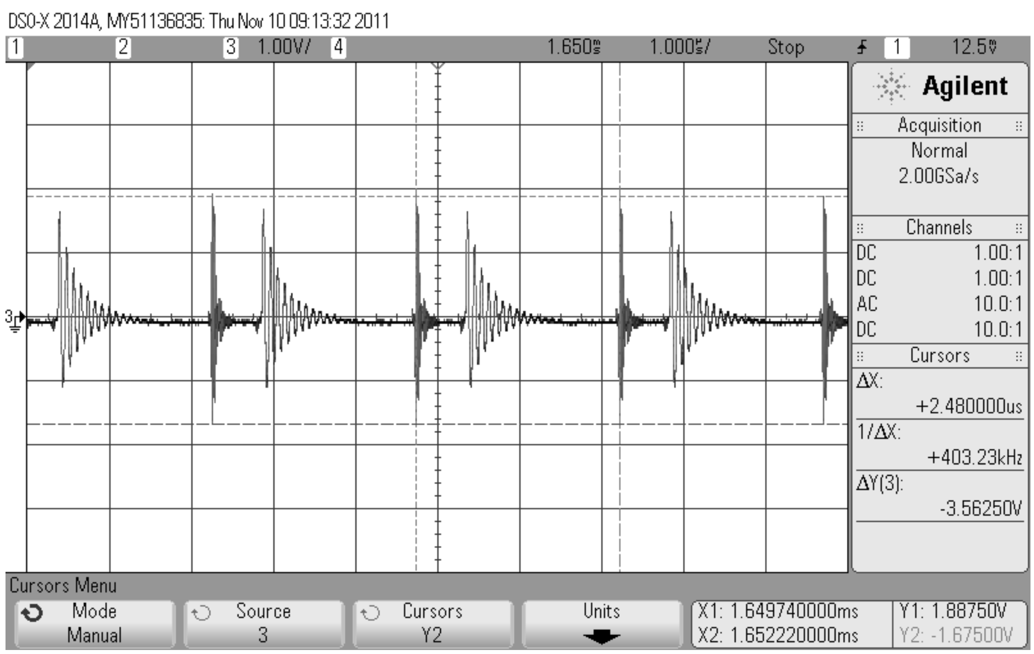

Figure 5.1. DC-DC Converter Output Oscilloscope Capture AC Coupled

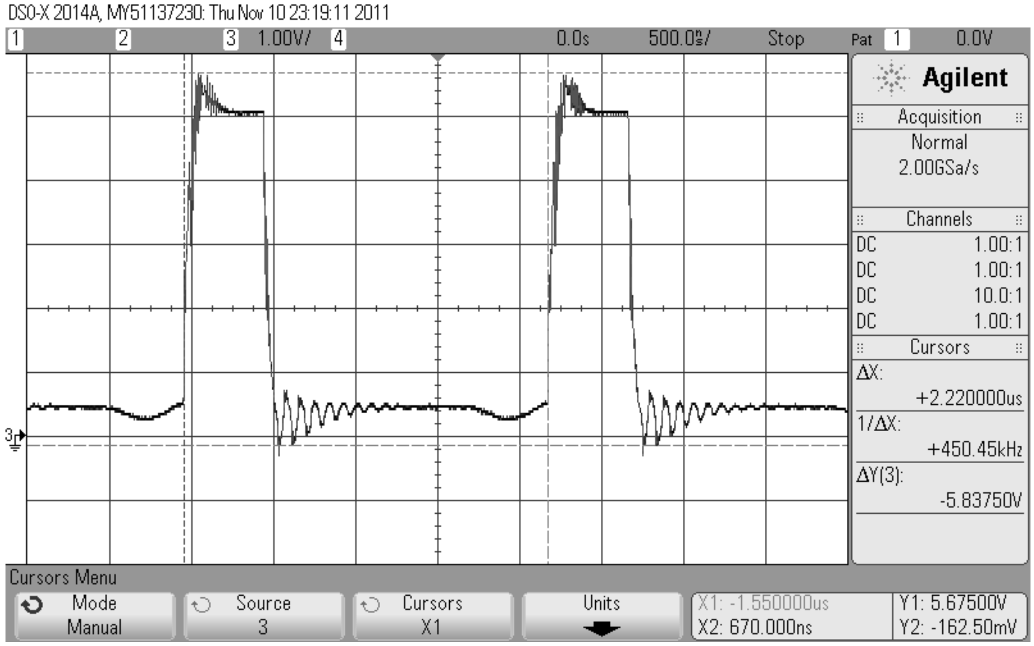

Figure 5.2. Gate Signal of MOSFET Oscilloscope Capture

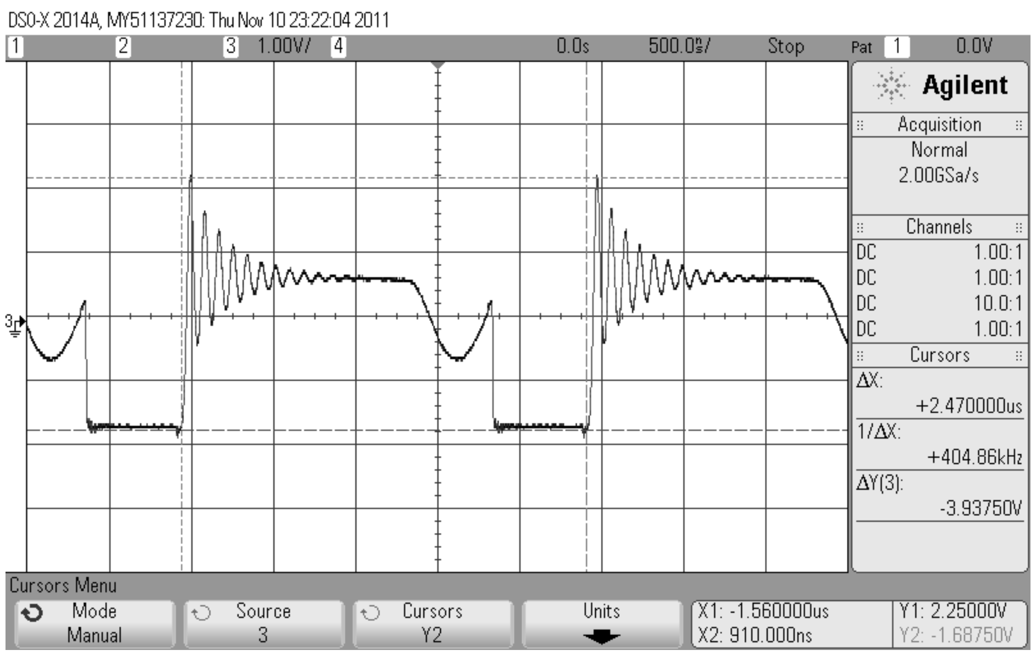

Figure 5.3. Drain Signal of MOSFET Oscilloscope Capture

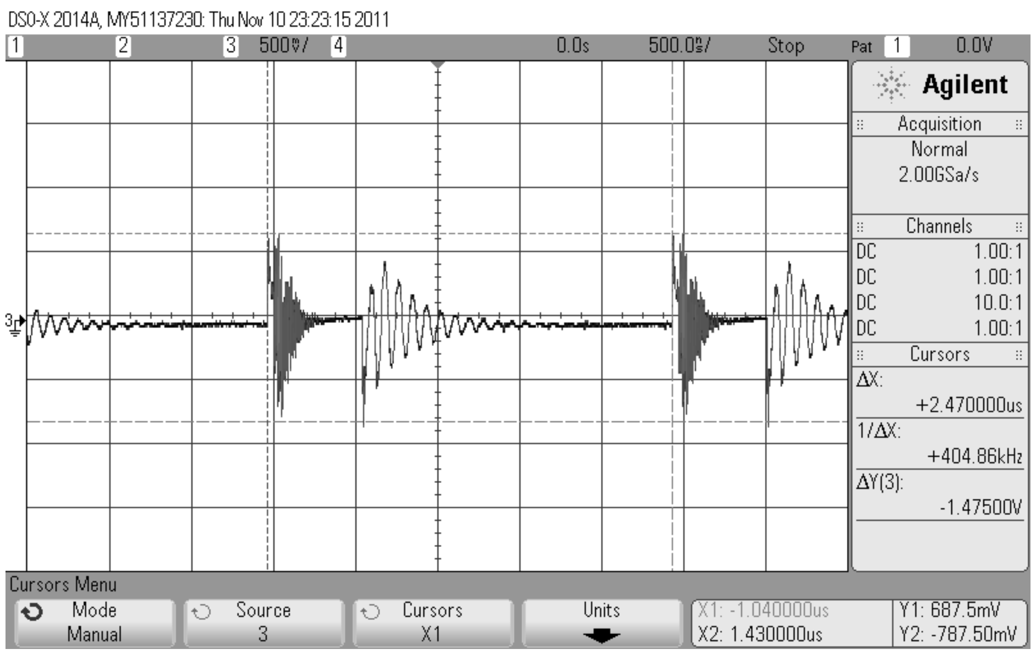

Figure 5.4. Source Signal of MOSFET Oscilloscope Capture

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